

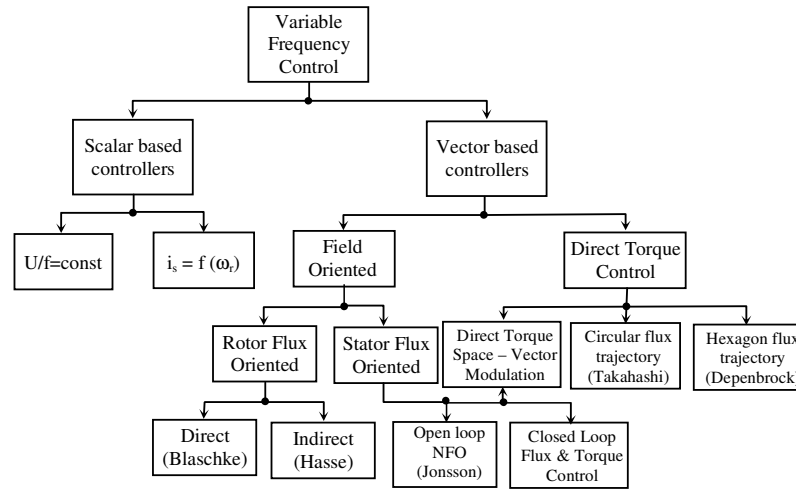
## CHAPTER 1

### INTRODUCTION

#### 1.1 A Look Back On Electrical Machine Drives

DC machines were used extensively in variable speed drive over the past decades mainly because of the decoupled control of flux and torque that could be achieved by the field and armature current control respectively. They are mostly used in variable speed applications to give a fast and good dynamic torque response because the commutator maintains a fixed (and nearly ideal) torque angle at all times. However, DC machines have two major weaknesses, the mechanical commutator and brush assembly. These make periodical maintenance a must and limit the use of DC machines in explosive environment.

Induction machines have several advantages over DC machines. They are robust, require less maintenance, cheaper, and operate at higher speed. Basically, induction machines control methods can be classified into scalar and vector control. In scalar control, only magnitude and frequency of voltage, current, and flux linkage space vectors are controlled. Where as, in vector control, the instantaneous positions as well as the magnitude and frequency of voltage, current, and flux linkage space vectors are controlled. A chart showing the hierarchy of variable frequency control of induction machine is given in Figure 1.1. Constant volt per hertz is a well-known scalar control method while Field Oriented Control (FOC) and Direct Torque Control (DTC) are the two most popular vector control methods.



**Figure 1.1 :** Classification of induction machines control methods

The invention of Field-Oriented Control (FOC) in early 1970 by F.Blaschke enables rugged induction machines to be controlled similar to that of DC machines [1]. The advent of fast microprocessors and DSPs make the vector control popular in the 1980's. It is believed that the AC machines are supplanting the DC machines in the near future [2].

FOC provides similar decoupled control of torque and flux, which is inherently possible in the DC machines. The motor input currents are adjusted to set a specific angle between fluxes produced in the rotor and stator windings. The rotor flux position angle with respect to the stator must be known in this control method. Once the flux angle is known, an algorithm performs the transformation by changing three-phase stator currents into the orthogonal torque and flux producing components [2]. These components are controlled in their d-q axis and an inverse transformation is used to determine the necessary three-phase currents or voltages.

Although the FOC enables an induction machine to attain fast torque response, some problems still exist. An accurate flux estimator had to be employed to ensure the estimated value used in calculation does not deviate from the actual value. Besides, the coordinate transformation had increased the complexity of this control method. In [3], it is highlighted that the inverter switching frequency, torque ripple,

and harmonic losses of the machine increase in the steady-state operation if the hysteresis-based current-controlled inverter is used.

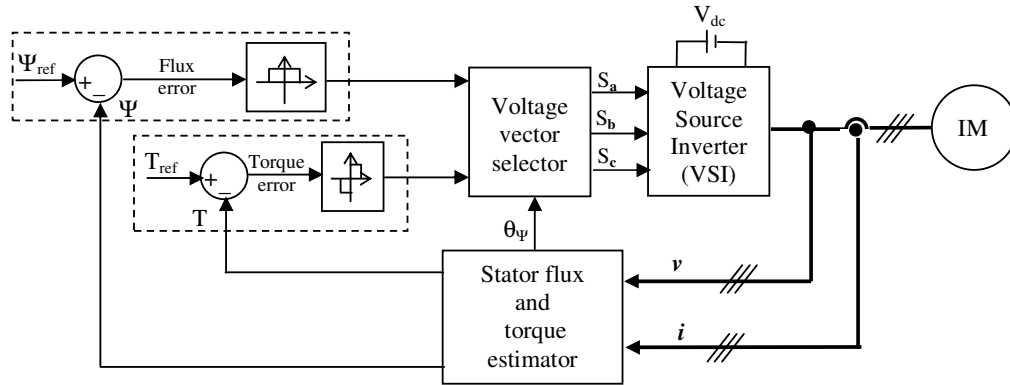
## **1.2 Direct Torque Control (DTC)**

Direct Torque Control was first introduced by Takahashi in 1986. The principle is based on limit cycle control and it enables both quick torque response and efficiency operation [3]. DTC control the torque and speed of the motor, which is directly based on the electromagnetic state of the motor [4]. It has many advantages compare to FOC, such as less machine parameter dependence, simpler implementation and quicker dynamic torque response [5]. It only needs to know the stator resistance and terminal quantities ( $v$  and  $i$ ) in order to perform the stator flux and torque estimations. The configuration of DTC is simpler than the FOC system due to the absence of frame transformer, current controlled inverter and position encoder, which introduces delays and requires mechanical transducer [6]. In [3], Takahashi had proved the feasibility of DTC compared to FOC.

In 1996, ABB has introduced the first industrial, speed-sensorless DTC induction motor drive. This simple control scheme has gained popularity and it is believed that they will soon replace the vector control drives commonly found in industry applications [7].

### **1.2.1 The Conventional DTC**

The basic configuration of the conventional DTC drive proposed by Takahashi is as shown in Figure 1.2. It consists of a pair of hysteresis comparator, torque and flux estimators, voltage vector selector and a Voltage Source Inverter (VSI) [3].



**Figure 1.2 :** Conventional DTC drive configuration

DTC performs separate control of the stator flux and torque, which is also known as decouple control. The core of this control method is to minimize the torque and flux errors to zero by using a pair of hysteresis comparators. The hysteresis comparators lie at the heart of DTC scheme not only to determine the appropriate voltage vector selection but also the period of the voltage vector selected. The performance of the system is directly dependent on the estimation of stator flux and torque. Inaccurate estimations will result in an incorrect voltage vector selection.

The basic method for estimating the stator flux is by using the stator voltage model. This model does not require rotor speed and only need a single machine parameter, i.e. the stator resistance. However, noise in voltage measurement and integration drift can pose significant problems at low speed [8]. Another method for estimating the stator flux is named current model. It solves the low speed problem but it needs to monitor the rotor speed. In other words, it requires additional speed sensor or observer. In [3], a combination of these 2 models had been proposed by using a simple lag network.

### 1.2.2 The Evolution Of DTC

Although DTC is gaining its popularity, there are some drawbacks, which need to be rectified. Variable switching frequency and high torque and flux ripples

are the two major problems, which draw full attention of most researchers. To overcome these problems, extensive research and development had been carried out.

In order to maintain the flux and torque error within the fixed hysteresis bands, the switching frequency becomes unpredictable. It is highlighted in [9] and [10] that the switching frequency varies with the operating speed, load condition and parameters of the induction machine. Hence, in order to ensure that the switching frequency does not exceed the limit, we have to calculate the extreme cases corresponding to the maximum switching frequency. Nevertheless the drive does not operate at these extreme cases in most of the time; therefore the maximum switching frequency capability is not fully utilized.

In order to overcome this problem, a number of methods had been proposed in the literature. Basically these can be divided into hysteresis based and non-hysteresis based solutions. In [11] variable hysteresis band comparators had been designed where the band can be adjusted to maintain constant switching frequency. For non-hysteresis based solutions, a few techniques have been proposed, including the use of space vector modulation, predictive control schemes and intelligent control techniques, which had been published in [12-17].

Another problem normally associated with DTC drive is the high torque ripple. Ideally, small torque hysteresis band will produce small torque ripple. However, for microprocessor-based implementation, if the hysteresis band is too small, the possibility for the torque to touch the upper band is increased. As a result, the possibility of selecting a reversed voltage vector instead of zero voltage vector will also increase. Incorrect voltage vector selection will result in high torque ripple. In [19], it is proved that by reducing the sampling time, the torque ripple can be reduced significantly. In addition, there are numerous techniques proposed to reduce the torque ripple such as dithering technique [20], fuzzy logic control [15], [16] and SVM [12]. A more details discussion is given in Chapter 2 on fixed switching frequency and torque ripple reduction.

### 1.3 Thesis Objective and Contributions

The objective of this thesis is to study, implement and improve the performance of the DTC of induction machines. The thesis proposes a simple method for torque and stator flux ripple reduction. Meanwhile, the constant switching frequency is increased to 10kHz. The simple control structure of the DTC drive is preserved. The contributions of this thesis are as follow:

- It proposes a torque controller, which had further minimized the torque ripple (80% of ripple reduction had been achieved compare to the hysteresis-based torque controller) and maintained a constant switching frequency at around 10 kHz.
- It introduces a simple flux controller to replace the two-level hysteresis comparator, which results in an almost circular stator flux locus with small ripple (achieve 57% of ripple reduction compare to the hysteresis-based flux controller).
- It reduces the Total Harmonic Distortion (THD) of the phase current since a more sinusoidal current wave is achieved by implementing the proposed flux controller.
- It performs simulations to verify and analyze the performance of the proposed torque and flux controllers using MATLAB/SIMULINK simulation package.
- It develops an experimental set-up to verify the proposed DTC drive. A combination of TMS320C31 DSP and FPGA device reduces the execution time.

However there are some constraints in this research:

- The feasibility of the proposed controllers is evaluated only in low speed region and low voltage due to laboratory equipment limitations.
- Equipment in laboratory is limited. The power supply can only support up to 120 V.
- The speed of the TMS320C31 DSP is limited to 60MHz.
- The duration and funding of this research are limited.

#### **1.4 Methodology of Research**

A simulation on the conventional DTC drive is performed for better understanding by using MATLAB/SIMULINK. With the understanding and knowledge of the conventional DTC, a new torque and flux controllers are proposed. The proposed controllers are then simulated to study on their effectiveness. Based on the simulation results, proper planning and prototype design are made.

Once the satisfactory simulation results are obtained, the hardware prototype are built and implemented. Hardware implementation is used to verify the feasibility of the proposed drive. It consists of three main components, a digital signal processor board DS1102 from dSPACE (TM320C31 at 60MHz), an Altera University Program (UP) Educational Board and the power circuit. The DSP is responsible for estimating the torque and stator flux. The proposed controllers are implemented using FPGA with Very high-speed integrated circuits, Hardware Description Language (VHDL). The power circuit consists of a 3-phase Voltage Source Inverter (VSI) connected to a ¼ HP induction machine. A friction load is coupled to the induction machine as a mechanical load.

Several tests are performed on the prototype of the DTC drive. Trouble-shoot, modifications, debug and improvements are carried out on the prototype until satisfactory tests results are obtained.

## 1.5 Thesis Organizations

A brief review of the contents of this thesis is given as follows:

**Chapter 2** presents the principle of DTC and modeling of induction machines in space vector form. Problems associated with DTC such as stator flux estimation, fixed switching frequency techniques and torque ripple reduction are also discussed.

**Chapter 3** proposes new flux and torque controllers, which reduce torque and flux ripples and produce constant switching frequency at around 10 kHz. The principles and design of the new controllers are discussed and implemented to a small induction machine.

**Chapter 4** evaluates the performance of the proposed controllers via simulation using MATLAB/SIMULINK simulation package. The descriptions on modeling of the proposed DTC drive using SIMULINK block are given.

**Chapter 5** describes the experiment set-up in this research. Detailed information of each hardware components is given.

**Chapter 6** gives all the simulation results, experimental results and discussions.

Lastly, **Chapter 7** gives the conclusions of the thesis and possible directions of further research.